New approach to discriminate between mass and particle species type behavior of ϕ meson at FAIR energies

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Abstract

In the study of heavy ion collision, ϕ meson is of special significance from the point of view that though it is a meson, at the same time has a mass comparable to baryons. Therefore a comparison of any parameter of ϕ with other baryons can help to differentiate between mass and particle species type dependence of particle production. The variation of width of the rapidity distribution on beam rapidity and the rapidity distribution of strangeness enhancement factor have been studied with UrQMD generated mesons and baryons at various FAIR energies to ascertain mass/species type behavior of ϕ meson. The width of the rapidity distribution is found to bear a power law with beam rapidity with a clear indication of violation of mass ordering at ϕ meson. Results on strangeness enhancement factor E_S of various strange particles also reveals a similar mass ordering violation at ϕ meson indicating particle nature of ϕ meson.

Keywords: Rapidity, strangeness enhancement, UrQMD, ϕ-meson.

1. Introduction

The proposed Compressed Baryonic Matter (CBM) experiment at the future facility for antiproton and ion research (FAIR) would be a dedicated heavy ion experiment operating in fixed target mode (Au+Au collision up to 45 AGeV) and is planned to explore the properties of nuclear matter at moderate temperature and high baryon density [1-3]. One of the characteristic features of FAIR is its high luminosity beam which would be suitable to study rare probes of such hot and dense medium. Experiments like CBM that would use large acceptance detectors would cover centre of mass rapidity to beam rapidity. For such detectors the evolution of the width of rapidity distribution as a function of beam energy and centrality would be of much significance [4]. The width of the rapidity distribution is believed to be sensitive to the final state re-scattering [5] which in turn is dependent on the mass of the produced particle [6-8].

Strange particles are produced only at the time of collisions and thus expected to carry important information of collision dynamics. Of all these strange particles, ϕ ($s\bar{s}$) meson, the lightest bound state of strange quark with hidden strangeness, is of particular importance as it has a very less interaction cross-section with non-strange hadrons [9] and therefore is expected to provide the undistorted information about the hot and dense medium [10]. There has been a long sought quest about the nature of ϕ [11], because, though ϕ is a meson, it, at the same time, has a mass comparable to baryons (e.g. p, Λ). It is believed that a study of the relation of particle production to its intrinsic property may reveal its production mechanism [12]. To ascertain if the nature of particle production is mass or type (meson/baryon) dependent, a number of observables have been studied both at SPS and RHIC energies [11, 13]. For example, Adams *et al.* [12] have studied nuclear modification factor of K^* for Au+Au collision at $\sqrt{s}$ = 200 GeV and observed that both R_{AA} and R_{CP} of K^* at intermediate p_t is similar to K^0_S but different from Λ. A number of other workers [11-18]

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have carried out similar measurements on nuclear modification factors R_{AA} and R_{CP} to probe production dynamics and hadronization process of HIC. Blyth *et al.* [11] (for STAR collaboration) have studied, for Au+Au collision at $\sqrt{s}$ = 200 GeV, elliptical flow v_2 at different p_t and nuclear modification factor R_{CP} of ϕ meson. From the results of their investigation it is inferred that at RHIC energy the particle production mechanism is species (meson/baryon) rather than mass dependent.

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) [19, 20] is a microscopic model based on a phase space description of p+p, p+A and A+A collisions that remains successful in describing the observables of heavy ion collisions over an energy range E_{lab} = 100 AMeV to $\sqrt{s}$ = 200 GeV [21]. At low and intermediate energies ($\sqrt{s} < 5$ GeV), it describes the phenomenology heavy ion collisions in terms of interactions between known hadrons and their resonances. At higher energies, $\sqrt{s}$ >5 GeV, the excitation of color strings and their subsequent fragmentation into hadrons are taken into account. In this model, strange hadrons in heavy ion collision may either be produced in the very early stage in the initial collisions among the incoming nucleons or in the later stage through secondary collisions among the produced particles [22]. In low energy domain i.e., close to threshold energy, strangeness can either be produced in NN reaction channel directly e.g. $p + p \longrightarrow p + \Lambda + K^+$ or in two step reaction such as $p + p \longrightarrow N + N^*_{1710}$ and finally $N^*_{1710} \longrightarrow Y + K^+$. At higher incident beam energies, particle production in general is dominated by string excitation and fragmentation [22]. About two-third of the ϕ mesons are produced in UrQMD via KK coalescence mechanism. At all energies, the string excitation and fragmentation is the only mechanism in UrQMD that can produce Ω.

In this work an attempt has been made, with UrQMD [19, 20] generated events at 10, 20, 30 and 40 AGeV, to investigate the mass/species type behavior of ϕ meson from a measurement on the width of the rapidity distribution and the rapidity dependence of strangeness enhancement factor of mesons and baryons.

2. Width of rapidity distribution of mesons and baryons

In heavy ion collision, rapidity (Y) or pseudorapidity (η) distribution are found to be quite informative of particle production mechanism [4, 23]. In figure 1, the rapidity distribution of a few hadrons such as π^-, k^+, k^-, ϕ and Λ produced in UrQMD generated Au+Au collisions at 10, 20, 30 and 40 AGeV are plotted and compared with the existing SPS (NA49) [24] and AGS (E877, E891, E896) [25, 26] data at the same energies. Though the generated data, at all energies, can reproduce the general trend of the experimental data, the yield of Λ and ϕ for UrQMD generated events are found to be somewhat less than the experimental results.

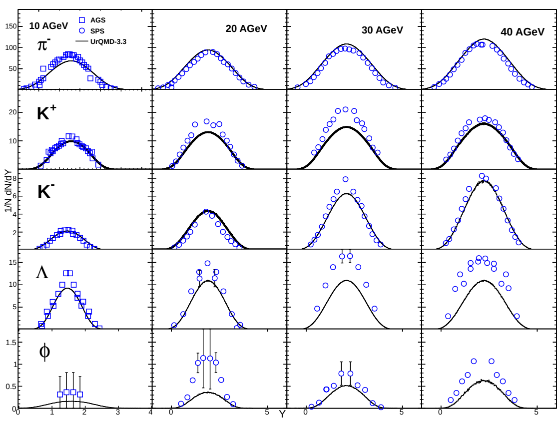

Figure 1: Rapidity distribution of produced particles ($\pi^-, k^+, k^-, \Lambda, \phi$) for four different beam energies E_{lab}= 10, 20, 30 and 40 AGeV is compared with the existing SPS (NA49) [24] and AGS (E877, E891, E896) [25, 26] data.

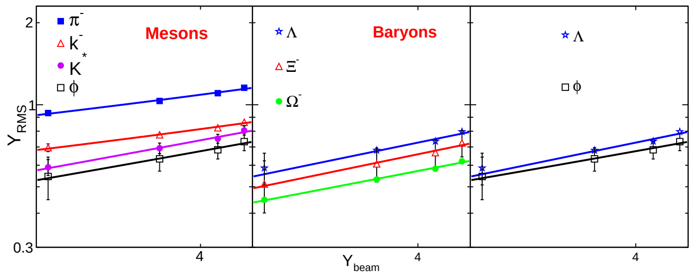

Figure 2: Variation of width of the rapidity distribution of mesons (left) and baryons (middle) as a function of beam rapidity in the lab system. In the right panel the same has been plotted separately for Λ and ϕ. The solid lines correspond to linear fits. The error bars shown here corresponds to the statistical error. For Ω^- the error bars are large and hence not shown in this figure.

As the width of the rapidity distribution is sensitive to final state re-scattering which in turn is dependent on the mass of the produced particles, a study on the width of the rapidity distribution on beam rapidity is expected to be relevant to provide more insight into the mass/type dependent nature of ϕ meson [5]. Figure 2 represents, in log-log scale, the width of the rapidity distributions as a function of beam rapidity in laboratory frame for studied mesons and baryons. As expected, the lighter particles have larger width. From this plot, a scaling behavior of the width of the rapidity distribution on beam rapidity is readily evident. The values of the exponent for the studied mesons and baryons are listed in table 1 and the variation of this exponent with the mass of the produced particles is shown in figure 3. The values of the exponent are found to increase linearly with the mass of the produced particle irrespective of its type (meson/baryon) indicating the mass dependence nature of the exponent value. It is interesting to note from figure 2 that mesons and baryons taken together do not follow mass ordering. Mass ordering breaks at ϕ meson. However, mesons and baryons separately follow mass ordering indicating the possibility of using mass ordering of the width of the rapidity distribution as a sensitive tool to ascertain mass/species type behavior of ϕ meson.

Table 1: Particle mass vs exponents

Particle	Mass $[GeV/c^2]$	Exponent	Error
π^-	0.14	0.628	0.01951
k^-	0.493	0.6475	0.1001
k^*	0.892	0.8427	0.2241
ϕ	1.020	0.887	0.529
Λ	1.115	1.028	0.1011
Ξ^-	1.321	1.035	0.6995
Ω^-	1.672	0.9952	–

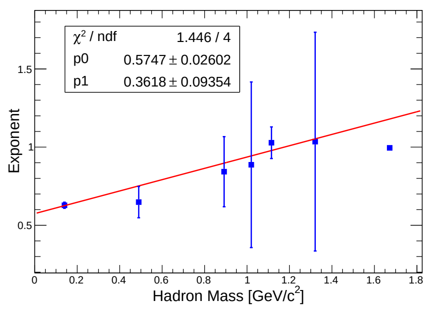

Figure 3: The variation of exponents with masses of the produced particles. The solid red line corresponds to a linear fit.

3. Strangeness enhancement

Strangeness enhancement is considered to be one of the traditional signatures [27, 28] of formation of QGP. However, such an enhancement was challenged by an alternate idea of canonical suppression [29] of strangeness in small systems like p+p or p+A collisions. The cause of such suppression is believed to be due to the phase space constraint in smaller system i.e. $s\bar{s}$ production will be less in p+p or p+A collisions. Further, there are a number of other different mechanism that might also result enhancement in strange and multi-strange baryons. One such mechanism is the superposition of color electric field that might occur in central heavy ion collision which in turn fragmented resulting enhanced production of heavy flavors [30-35].

Strangeness enhancement factor E_S is quantified by measuring the ratio of yield of strange particles in A+A collision and respective yield in p+p or p+A collisions, where both the numerator and denominator should be properly normalized by the number of participants (N_{part}). However, such enhancement depends strongly on the kinematical restrictions. The conventional definition of strangeness enhancement factor is [36].

$$E_s = \frac{(Yield)_{AA}}{< N_{part} >} / \frac{(Yield)_{pp(pA)}}{< N_{part} >} \tag{1}$$

For this report, following the reference [37], the strangeness enhancement factor E_S is defined as -

$$E_S = [\frac{(Yield)_{AA}}{< \pi^- >}]_{central} / [\frac{(Yield)_{AA}}{< \pi^- >}]_{peripheral} \tag{2}$$

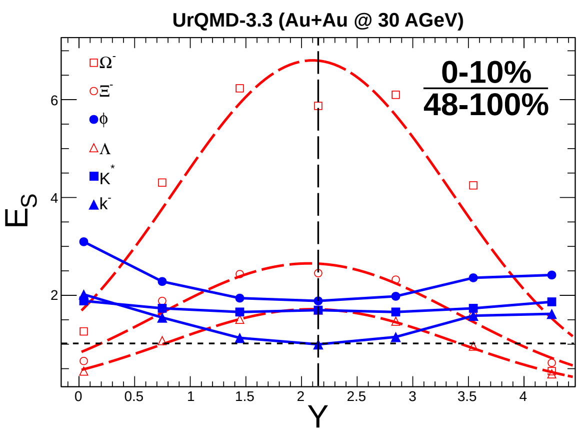

Figure 4: Strangeness enhancement factor E_S as a function of rapidity for Ω^-, Ξ^-, ϕ, Λ, K^* and k^- at 30 AGeV. The red dashed curves correspond to gaussian fits while solid blue curves are drawn to guide the eyes.

E_S has been estimated as a function of rapidity for both strange hyperons (Λ, Ξ^- and Ω^-) and strange mesons (k^-, K^* and ϕ) at the incident beam energy 30 AGeV and is shown in figure 4. From this figure it can be readily seen that the enhancement at mid-rapidity increases with the strange quark content but does not follow a mass ordering. Again, the mass ordering violates at ϕ meson. Further, it is interesting to note that the patterns of variation of enhancement factor E_S for the studied mesons and baryons are completely different. For baryons, as expected, E_S is maximum at mid-rapidity and minimum at beam and target rapidities while for mesons, the situation is otherwise. Similar behavior has been observed at other FAIR energies viz. 10, 20 and 40 AGeV as well.

4. Summary

This study on the width of the rapidity distribution of mesons and baryons produced in central Au+Au collisions at 10, 20, 30 and 40 AGeV using UrQMD model reveals a power law behavior on beam rapidity. The values of the exponent are found to be dependent more on the mass rather than the type of the particles. The observed violation

of mass scaling of the width of the rapidity distribution with beam rapidity at ϕ meson indicates the possibility of considering this parameter as a sensitive tool to discriminate the mass/species type behavior of ϕ meson. Similarly, E_S, when plotted with Y, also violets the mass scaling if ϕ meson is included. Further, the rapidity distribution of E_S of strange mesons and baryons are found to be completely different. For strange baryons the enhancement is found to be maximum at mid rapidity while for strange mesons maximum enhancement is found to be at beam and target rapidities. Such behavior is also indicative of the consideration of rapidity distribution of enhancement factor as yet another sensitive tool to discriminate the mass/species type behavior of ϕ meson.

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